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# JOINT ROUTING AND WAVELENGTH ASSIGNMENT IN WDM NETWORKS FOR PERMANENT AND RELIABLE PATHS

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## ABSTRACT

In this paper, we tackle the routing and wavelength assignment problem for wavelength division multiplexing (WDM) networks containing permanent and reliable wavelength paths (WPs). This problem consists of finding the routes and the wavelength for each WP for the normal state of the network and for the important failure scenarios. These scenarios might be the most probable failure scenarios or simply the failure scenarios of interest of the network planner (e.g., the single link failure scenarios). We propose a mathematical programming model for this problem. In order to find a solution within a reasonable amount of time, heuristic algorithm is proposed. The results show that quasi-optimal solutions can be obtained with the proposed heuristic algorithm.



**Keywords**: Optical network planning, wavelength division multiplexing, wavelength path routing, wavelength assignment, mathematical model, heuristic algorithm.



## RÉSUMÉ

Dans cet article, nous traitons du problème du routage et de l'affectation des longueurs d'ondes dans les réseaux optiques WDM (*Wavelength Division Multiplexing*) contenant des WPs (*Wavelength Paths*) permanents et robustes. Premièrement, nous proposons un modèle pour ce problème et ensuite, dans le but de trouver de bonnes solutions rapidement, nous proposons une heuristique considérant les pannes simples de liens dans le réseau. Les résultats montrent que de bonnes solutions sont obtenues avec cette heuristique.



**Mots-clés** : Planification des réseaux optiques, multiplexage de longueurs d'ondes, acheminement des chemins, affectation des longueurs d'ondes aux chemins, modèle mathématique, heuristique.

# 1 Introduction

The WDM network planning process is a long and complex process that consists, broadly speaking, of designing the network topology, routing the lightpaths, assigning wavelengths to lightpaths and link dimensioning (i.e., allocating capacity and spare capacity). The planning of physical fault restoration mechanisms, such as (1+1) and (1:N) optical protections, and the planning of self-healing optical rings should also be included in that process. (For a review of each of these steps, see Stern and Bala [16].)

In this paper, we consider the joint routing and wavelength assignment (RWA) problem for reliable WDM networks. This problem includes the routing and wavelength assignment steps of the general WDM network planning process.

Two types of WPs are considered, the permanent and reliable WPs. Permanent WPs are the first form of WP. Actually, a backup WP provisioned on a diversified path provides the reliability of a permanent WP. If there is a failure on the network that affects the permanent WP, the traffic is rerouted on the backup path. In fact, there is no fundamental reason why WPs could not be automatically rerouted upon failures. This is what is being done for reliable WPs.

In this paper, we introduce the RWA problem considering both permanent and reliable WPs. This problem consists of finding the routes and the wavelength assignment for the normal state of the network and for the important failure scenarios. These scenarios might be the most probable failure scenarios or simply the failure scenarios of interest to the network planner (e.g., the single link failure scenarios or the single node failure scenarios). The objective is to minimize the number of blocked WPs. The shortest path routing mechanism is

considered to route the WPs. From the implementation simplicity and the route calculation performance perspective, this type of routing is the best one [3, 5].

The literature contains many papers on the RWA problem (for instance, see [6,10, 12,13,15]) and on the general WDM planning process (for instance, see [4,8,11,16]). However, only references [6,11,12,13] have considered the reliability in the WDM network design process. Indeed, Gangxiang *et al.* [6] have suggested two strategies for path protection in WDM networks: One for path protection without spare capacity sharing and another that allows the spare capacities to be shared. Heuristic algorithms for efficiently determining the working and protection lightpaths have been proposed. Lee *et al.* [11] have investigated the routing and planning of working capacity and spare capacity in WDM networks. A joint optimization technique has been used and the problem has been formulated to restore the general failure scenarios. Miyao and Saito [12] have proposed an optimal design scheme for survivable WDM networks in which fast restoration can be achieved by using predetermined restoration paths that are independent of failure locations and which have one to one correspondence with working paths. An integer programming-based design model has been formulated to optimally determine working and their corresponding restoration paths, the number of fibers in each span, and the number of optical cross connects in each node. Mohan *et al.* [13] have considered the problem of establishing dependable connections in WDM networks. A dependable connection (also called a D-connection) is similar to a reliable WP, except that the reliability of a D-connection is achieved with a primary and a backup lightpath. The backup lightpath is setup only when the primary lightpath has failed, allowing the multiplexing of backup channels. The authors have developed algorithms to select routes

and wavelengths to establish D-connections with improved blocking performance the single failure scenarios.

In this paper, it is the first time the permanent and the reliable WPs are considered within the RWA problem. As mentioned before, no backup paths are reserved for the reliable WPs. The reservation is done at the wavelength level. As a result, a reserved wavelength can be used by several reliable WPs in different failure scenarios.

The paper is organized as follows. Section 2 proposes a mathematical programming model for the RWA problem considering both permanent and reliable WPs. The proposed model is adapted for the single link failure and for the single node failure scenarios. Section 3 presents a heuristic algorithm to find approximate solutions of the model. In Section 4, numerical results are presented. Conclusions and further works are discussed in Section 5.

## 2 The Model

In this section, we present a mathematical programming model for the RWA problem.

### 2.1 Assumptions

The following assumptions are made: (A1) The same wavelength is used from the origin to the destination of each WP; (A2) The routing of the WPs is based on a weighted shortest path policy; (A3) The network topology is bi-connected; (A4) The links are bi-directional.

### 2.2 The Notation

The following notation is used throughout the paper.

*Sets:* Let $N$ be the set of optical nodes in the networks and $M$, the set of links. Let $K$ be the set of WPs such that $K = K^P \cup K^R$ where $K^P$ is the set of permanent WPs and $K^R$, the set of reliable WPs, $O(k)$, the origin node of the WP $k \in K$ and $D(k)$, the destination node of the WP $k \in K$. Let $\Omega$ be the set of available wavelengths, $\Omega_{ij}$, the set of available

wavelengths on link $(i, j) \in M$ and $T$, the set of network states considered that contain the no failure scenario (the state $t_0$) and the failure scenarios (the states 1 to $t_{|T|-1}$), e.g., the most probable failure scenarios or the ones of interest to the network planner.

*Decision Variables:* Let $x_{ij}^{kt\lambda}$ be a 0–1 variable such that $x_{ij}^{kt\lambda} = 1$ if and only if the WP $k \in K$ use the wavelength $\lambda \in \Omega_{ij}$ and pass on the link $(i, j) \in M$ in the network state $t \in T$, $b^{kt}$, a 0–1 variable such that $b^{kt} = 1$ if and only if the WP $k \in K$ is blocked in the network state $t \in T$, $c_\lambda^{kt}$, a 0–1 variable such that $c_\lambda^{kt} = 1$ if and only if the WP $k \in K$ use the wavelength $\lambda \in \Omega$ in the network state and $d_j^{kt}$, the length of the shortest path from $O(k)$ to node $j \in N$ in the network state $t \in T$.

*Routing Parameters:* Let $a_{ij}$ be the routing metric on link $(i, j) \in M$.

**2.3 The Model**

The model for the RWA problem considering both permanent and reliable paths, denoted P, is presented below.

$$\text{P:} \quad \min_{\mathbf{x},\mathbf{b},\mathbf{c}} \sum_{t \in T} \sum_{k \in K} b^{kt} \tag{1}$$

subject to

*Shortest path constraints (for the permanent WPs)*

$$\begin{aligned} & d_j^{kt} = 0 && (j = O(k), k \in K^P, t = t_0) \\ & d_j^{kt} \le d_i^{kt} + a_{ij} \sum_{\lambda \in \Omega_{ij}} x_{ij}^{kt\lambda} && (k \in K^P, t = t_0, (i, j) \in M) \end{aligned} \tag{2}$$

*Shortest path constraints (for the reliable WPs)*

$$\begin{aligned} & d_j^{kt} = 0 && (j = O(k), k \in K^R, t \in T) \\ & d_j^{kt} \le d_i^{kt} + a_{ij} \sum_{\lambda \in \Omega_{ij}} x_{ij}^{kt\lambda} && (k \in K^R, t \in T, (i, j) \in M) \end{aligned} \tag{3}$$

*Wavelength uniqueness constraints*

$$\sum_{k\in K} x_{ij}^{kt\lambda} \le 1 \quad ((i,j)\in M, \lambda \in \Omega_{ij}, t \in T) \tag{4}$$

$$\sum_{\lambda\in\Omega} c_{\lambda}^{kt} \le 1 \quad (k \in K^P, t = t_0) \tag{5}$$

$$\sum_{\lambda\in\Omega} c_{\lambda}^{kt} \le 1 \quad (k \in K^R, t \in T) \tag{6}$$

$$x_{ij}^{kt\lambda} \le c_{\lambda}^{kt_0} \quad ((i,j)\in M, \lambda \in \Omega_{ij}, k \in K^P, t \in T) \tag{7}$$

$$x_{ij}^{kt\lambda} \le c_{\lambda}^{kt} \quad ((i,j)\in M, \lambda \in \Omega_{ij}, k \in K^R, t \in T) \tag{8}$$

*Path conservation constraints*

$$\sum_{(i,j)\in M}\sum_{\lambda\in\Omega_{ij}} x_{ij}^{kt\lambda} - \sum_{(j,i)\in M}\sum_{\lambda\in\Omega_{ji}} x_{ji}^{kt\lambda} = \begin{cases} 1-b^{kt} & \text{if } j \in D(k) \\ b^{kt}-1 & \text{if } j \in O(k) \\ 0 & \text{otherwise} \end{cases} \quad (j \in N, k \in K, t \in T) \tag{9}$$

*Failure scenario constraints*

| Failure scenario constraints | (10) |
|---|---|

*Integrality and nonnegativity constraints*

$$\mathbf{x} \in \{0,1\}^{|M||K||T||\Omega|}, \mathbf{b} \in \{0,1\}^{|K||T|}, \mathbf{c} \in \{0,1\}^{|K^P||T||\Omega|}, \mathbf{d} \in R_+^{|M|(|K^P|+(|K^R||T|))}. \tag{11}$$

The objective function of the model P, as mentioned before, is the total number of blocked WPs for all network states considered. Constraints (2) and (3) impose respectively the permanent and the reliable WPs be routed according to the shortest paths (considering the routing metric of each link). Constraints (4) to (8) are the wavelength uniqueness constraints. Constraints (4) impose that each wavelength is used by only one WP, constraints (5) impose each WP to use the same wavelength from its origin to its destination, constraints (7) and (8)

induce that each WP uses one wavelength by link. Constraints (9) are the path conservation constraints whereas constraints (10) are the failure scenarios constraints. These constraints can be the most probable scenarios constraints or simply the failure scenarios of interest to the network planner. Constraints (11) are the integrality and nonnegativity constraints.

Suppose that the network planner wants to consider the single link failure scenarios. If we note $\{(i,j)\in M : i<j\} = \{(i_1,j_1),(i_2,j_2),...,(i_{|M|/2},j_{|M|/2})\}$ and suppose that the link $(i_l,j_l)$ is failed (in both directions) in the network state $t_l$ for $l=1$ to $|M|/2$, constraints (10) are

$$\begin{aligned} x_{i_1 j_1}^{kt_1\lambda} = 0,\ x_{j_1 i_1}^{kt_1\lambda} = 0 \quad & (\lambda\in\Omega_{i_1 j_1}) \\ x_{i_2 j_2}^{kt_2\lambda} = 0,\ x_{j_2 i_2}^{kt_2\lambda} = 0 \quad & (\lambda\in\Omega_{i_2 j_2}) \\ \vdots & \\ x_{i_{|M|/2} j_{|M|/2}}^{kt_{|M|/2}\lambda} = 0,\ x_{j_{|M|/2} i_{|M|/2}}^{kt_{|M|/2}\lambda} = 0 \quad & (\lambda\in\Omega_{i_{|M|/2} j_{|M|/2}}) \end{aligned} \tag{13}$$

for all $k\in K^R$,

$$\begin{aligned} x_{ij}^{kt_1\lambda} &\le 1 - \sum_{\lambda'\in\Omega_{i_1 j_1}} \left( x_{i_1 j_1}^{kt_0\lambda'} + x_{j_1 i_1}^{kt_0\lambda'} \right) \\ x_{ij}^{kt_2\lambda} &\le 1 - \sum_{\lambda'\in\Omega_{i_2 j_2}} \left( x_{i_2 j_2}^{kt_0\lambda'} + x_{j_2 i_2}^{kt_0\lambda'} \right) \\ &\vdots \\ x_{ij}^{kt_{|M|/2}\lambda} &\le 1 - \sum_{\lambda'\in\Omega_{i_{|M|/2} j_{|M|/2}}} \left( x_{i_{|M|/2} j_{|M|/2}}^{kt_0\lambda'} + x_{j_{|M|/2} i_{|M|/2}}^{kt_0\lambda'} \right) \end{aligned} \tag{14}$$

for all $k\in K^P$, $(i,j)\in M$ and $\lambda\in\Omega_{ij}$, and

$$
\begin{aligned}
x_{ij}^{kt_1\lambda} &\geq x_{ij}^{kt_0\lambda}\left(1-\sum_{\lambda'\in\Omega_{i_1j_1}}\left(x_{i_1j_1}^{kt_0\lambda'}+x_{j_1i_1}^{kt_0\lambda'}\right)\right)\\
x_{ij}^{kt_2\lambda} &\geq x_{ij}^{kt_0\lambda}\left(1-\sum_{\lambda'\in\Omega_{i_2j_2}}\left(x_{i_2j_2}^{kt_0\lambda'}+x_{j_2i_2}^{kt_0\lambda'}\right)\right)\\
&\vdots\\
x_{ij}^{kt_{|M|/2}\lambda} &\geq x_{ij}^{kt_0\lambda}\left(1-\sum_{\lambda'\in\Omega_{i_{|M|/2}j_{|M|/2}}}\left(x_{i_{|M|/2}j_{|M|/2}}^{kt_0\lambda'}+x_{j_{|M|/2}i_{|M|/2}}^{kt_0\lambda'}\right)\right)
\end{aligned}
\tag{15}
$$

for all $k\in K^P$, $(i,j)\in M$ and $\lambda\in\Omega_{ij}$.

Constraints (13) impose for each state of the network that all reliable WPs to pass around the failed link, constraints (14) necessitate each permanent WP passing through a failed link to be inoperative and constraints (15) require the other WPs to stay operational. Similar constraints can be easily written down for the single node failure scenarios.

P is NP-hard (transformation from the graph-coloring problem [7]). As a result, it is unlikely that large-size instances of P be solved to optimality within a reasonable amount of time.

In the next section, a heuristic algorithm is proposed to find approximated solutions of the model.

## 3 The Heuristic

The heuristic algorithm proposed in this section, denoted H, is designed to find "good" feasible solutions of P within a reasonable amount of time. The algorithm H is presented below.

**Algorithm H**

**Step 1:** (*The normal state of the network*)

**Step 1.1:** (*Find the shortest paths in the network*)

For all $i, j \in N$, find a shortest path between node $i$ and node $j$ considering the routing link metrics $a_{ij}$ for all $(i, j) \in M$.

**Step 1.2:** (*Find the routing of the WPs*)

For all $k \in K$, route the WP $k$ according to the shortest path found in Step 1.1.

**Step 1.3:** (*Assign the wavelength to the WPs*)

For all $k \in K$, assign a wavelength (denoted $\lambda(k)$) to WP $k$ considering the wavelength uniqueness constraints. If a wavelength has been found for WP $k$, set $b^{kt_0} := 0$, $c^{kt_0}_{\lambda(k)} := 1$ and $c^{kt_0}_{\lambda} := 0$ for all $\lambda \in \Omega \setminus \{\lambda(k)\}$. Otherwise, if there exists another shortest path for WP $k$ try it, otherwise set $b^{kt_0} := 1$ and $c^{kt_0}_{\lambda} := 0$ for all $\lambda \in \Omega$.

**Step 1.4:** (*Set the $x^{kt_0\lambda}_{ij}$ variables*)

For all $k \in K$ and $(i, j) \in M$ do

**Step 1.4.1:** If WP $k$ passes trough link $(i, j)$, set $x^{kt_0\lambda(k)}_{ij} := 1$. Otherwise set $x^{kt_0\lambda(k)}_{ij} := 0$.

**Step 1.4.2:** For all $\lambda \in \Omega_{ij} \setminus \{\lambda(k)\}$ set $x^{kt_0\lambda}_{ij} := 0$.

**Step 2:** (*The failure scenarios*)

For all $t := t_1$ to $t_{|T|-1}$ do

**Step 2.1:** (*Find the routing of the permanent WPs*)

For all $k \in K^P$, if the WP $k$ passes trough one or more failed network elements (in the scenario $t$), set $b^{kt} := 1$, $c^{kt}_{\lambda} := 0$ for all $\lambda \in \Omega$ and $x^{kt\lambda}_{ij} := 0$ for all $(i, j) \in M$ and $\lambda \in \Omega_{ij}$

Otherwise, set $x^{kt\lambda}_{ij} := x^{kt_0\lambda}_{ij}$ for all $(i, j) \in M$ and $\lambda \in \Omega_{ij}$

**Step 2.2:** (*Find the routing of the reliable WPs*)

**Step 2.2.1:** For all $k \in K^R$, if WP $k$ does not pass trough a failed network element, set $b^{kr} := 0$, $c_{\lambda}^{kr} := c_{\lambda}^{kr_0}$ for all $\lambda \in \Omega$ and $x_{ij}^{kr\lambda} := x_{ij}^{kr_0\lambda}$ for all $(i, j) \in M$ and $\lambda \in \Omega_{ij}$.

**Step 2.2.2:** For all $k \in K^R$, if WP $k$ passes trough one or more failed network elements, route the WP $k$ from node $O(k)$ to node $D(k)$ using the shortest path.

**Step 2.2.3:** For all rerouted WPs $k \in R^R$ in Step 2.2.2, assign a wavelength (denoted $\lambda(k)$) to WP $k$ considering the wavelength uniqueness constraints and the wavelengths already assigned. If a wavelength has been found for WP $k$, set $b^{kr} := 0$, $c_{\lambda(k)}^{kr} := 1$ and $c_{\lambda}^{kr} := 0$ for all $\lambda \in \Omega \setminus \{\lambda(k)\}$. Otherwise, if there exists another shortest path for WP $k$ try it, otherwise set $b^{kr} := 1$ and $c_{\lambda}^{kr} := 0$ for all $\lambda \in \Omega$.

**Step 3:** (*Termination*)

Return the vectors **b**, **c**, and **x**. The solution value is given by equation (1).

This heuristic considers the problem in two main steps. Step 1 finds the routing and the wavelength assignment (WA) for the normal state of the network (i.e., the no failure scenario) and Step 2 finds the routing and the WA for the other states of the network (i.e., for all the failure scenarios). Steps 1.1 and 1.2 find the routing of the permanent and reliable WPs in the normal state of the network. The routing is found according to the shortest paths (considering the routing metric of each link) that can be found using the Dijkstra algorithm (for more details about the shortest path problem, see Stern and Bala [16]). The WA problem of Step 1.3 is NP-hard (transformation from the graph-coloring problem). As a result, the WA problem should be solved approximately using heuristics. In this paper, since one WA problem should be solved per network state and the number of states may be large (a few hundreds), a simple heuristic is used (see [1,2,14,17] and the references contained therein for

mode details on the graph-coloring problem, the frequency and wavelength assignment problems and heuristics). The WA problem is transformed into the associate graph-coloring problem and the colors (i.e., the wavelength) are assigned one after another while respecting the uniqueness constraints. The $|K|$ different starting nodes are explored. Step 2.1 finds the routing for the permanent WPs for the failure scenarios and the Step 2.2 for the reliable WPs.

**3.1 Post-Optimization Algorithm**

The post-optimization algorithm eliminates the most penalizing WPs in order to minimizing the total number of blocked WPs, but the number of eliminated WPs must be inferior or equal to the initial number of blocked WPs, called $b_0$. In order to select the WPs to eliminate, we use an estimator, denoted $n_k$, of the required number of wavelengths to establish a WP $k$. Because finding the number of required wavelengths is also an NP-hard problem, we consider a lower bound proposed in [16]. Let $d(o,d)$ be the distance in optical hops between the origin $o$ to the destination $d$ and $\sum^d$ the total inter-nodal distance for the WP set, such that

$$\sum^d = \sum_{i=1}^{|K|} d(o_i, d_i) \tag{16}$$

Let $f$ be the number of optical fibres per link and $w$, the number of wavelengths per optical fibre. That means there are $|M|fw$ link-channels available. Since the minimum network capacity we need is $\sum^d$ link-channels, we obtain

$$w \geq \frac{\sum^d}{|M|f} \quad m \neq 0, f \neq 0 \tag{17}$$

We obtain a lower bound for the required number of wavelengths. As a result, we set $n_k = \sum^d$ since we use this bound to compare WPs and $f$ is a constant.

At each iteration of the post-optimization algorithm, we eliminate the WP with the larger value of $n_k$ and we find a new WA as described before. This method can only be applied to the normal state of the network since for the failure scenarios, we do not want to change the wavelength of a WP that has not been affected by a failure. This post-optimization algorithm applied to algorithm H will be denoted algorithm H+.

Note that this post-optimization algorithm could be applied to any WA algorithms, for instance, see [1,2,14,17].

## 4 Numerical Results

In this section, we evaluate the performance of the proposed algorithms H and H+. The algorithms were implemented in the C language on a Pentium 4 (1.6 GHz and 512 MB of RAM) computer. For the tests, seven test networks are used (see TABLE I)

TABLE I
TEST NETWORKS

| Network | Number of nodes | Number of links |
|---|---|---|
| N1 | 5 | 7 |
| N2 | 10 | 15 |
| N3 | 20 | 25 |
| N4 | 30 | 37 |
| N5 | 40 | 47 |
| N6 | 60 | 70 |
| N7 | 80 | 100 |

For the tests, the routing metric $a_{ij}$ is set to one for all links $(i, j) \in M$ and the number of wavelengths on each link is 1, 2, 4, 8, 16, 32 or 64. The WP traffic demand is generated as follows. For all pair of nodes, there is a permanent WP with probability $p_P$ and a reliable WP with probability $p_R$. In this paper, we consider $p_P = p_R = p$.

### 4.1 Comparison Between H and H+

FIG. I to III show the comparison between H and H+ respectively for test network N3, N5 and N7 and different values of $p$.

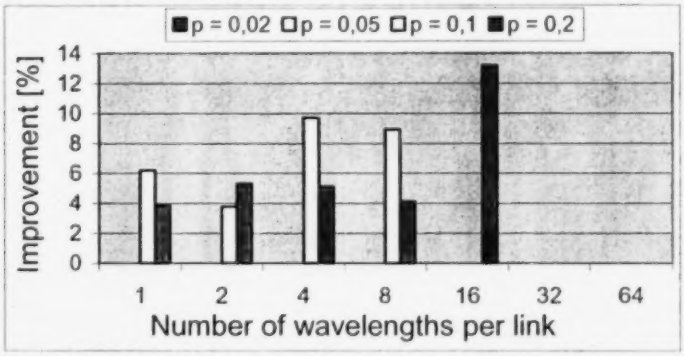


FIG. I. Percentage of improvement for test network N3

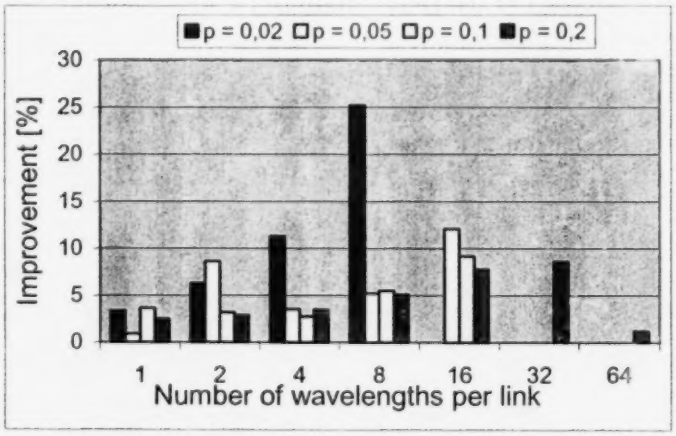


FIG. II. Percentage of improvement for test network N5

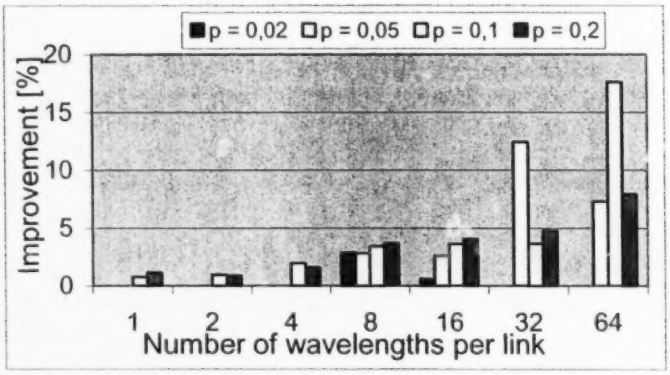


FIG. III. Percentage of improvement for test network N7

The following observations can be made from FIG. I to III. First, no improvement can be realized if there are enough wavelengths in the network for all the WPs in the different network states. On the other hand, if the number of wavelengths per link is small, the improvement is also small due to the network saturation.

**4.2 Performance of Algorithm H+ (for the No Failure State)**

H+ results were compared to a lower bound (denoted LB1) obtained as follows. The bound LB1 was obtained by using the CPLEX Mixed Integer Solver [9] to solve problem P but considering only the no failure state of the network. We have tried to solve P to optimality but we did not succeed to solve it using CPLEX.

TABLES II to VI present the values obtained with H+ (considering only the no failure state of the network) and LB1 as well as the CPU execution time.

TABLE II
NUMBER OF BLOCKED WPS (TEST NETWORK N2, $p = 0,1$)

| Number of wavelengths per link | Number of blocked WPs | | CPU [sec] | |
|---|---|---|---|---|
| | H+ | LB1 | H+ | LB |
| 1 | 4 | 4 | <1 | <1 |
| 2 | 1 | 0 | <1 | <1 |
| 4 | 0 | 0 | <1 | <1 |
| 8 | 0 | 0 | <1 | <1 |

TABLE III
NUMBER OF BLOCKED WPS (TEST NETWORK N2, $p = 0,2$)

| Number of wavelengths per link | Number of blocked WPs | | CPU [sec] | |
|---|---|---|---|---|
| | H+ | LB1 | H+ | LB |
| 1 | 25 | 25 | <1 | <1 |
| 2 | 13 | 12 | <1 | 8 |
| 4 | 2 | 1 | <1 | 8 |
| 8 | 0 | 0 | <1 | 4 |

TABLE IV
NUMBER OF BLOCKED WPS (TEST NETWORK N3, $p = 0,1$)

| Number of wavelengths per link | Number of blocked WPs | | CPU [sec] | |
|---|---|---|---|---|
| | H+ | LB1 | H+ | LB |
| 1 | 59 | 57 | <1 | 4 |
| 2 | 48 | 43 | <1 | 60 |
| 4 | 26 | 22 | <1 | 2 492 |
| 8 | 8 | 3 | <1 | 2 309 |

TABLE V
NUMBER OF BLOCKED WPS (TEST NETWORK N3, $p = 0,2$)

| Number of wavelengths per link | Number of blocked WPs | | CPU [sec] | |
|---|---|---|---|---|
| | H+ | LB1 | H+ | LB |
| 1 | 128 | 126 | <1 | 12 |
| 2 | 112 | 107 | <1 | 450 |
| 4 | 84 | 75 | <1 | 15 583 |
| 8 | 44 | 32 | <1 | 267 416 |

TABLE VI
NUMBER OF BLOCKED WPS (TEST NETWORK N4, $p = 0,1$)

| Number of wavelengths per link | Number of blocked WPs | | CPU [sec] | |
|---|---|---|---|---|
| | H+ | LB1 | H+ | LB |
| 1 | 137 | 136 | <1 | 22 |
| 2 | 121 | 115 | <1 | 4 964 |
| 4 | 99 | 89 | <1 | 16 569 |
| 8 | 71 | 57 | 2 | 270 |

The following observations can be made from TABLE II to VI. First, algorithm H+ finds solutions close to the lower bound values for the problems considered (within 8,63%, on average, from the lower bound) and the CPU time is less than or equal to 2 seconds. Moreover, the reader should point out that the heuristic finds the optimal solution five times.

**4.3 Performance of Algorithm H+ (for All States)**

First, we propose a lower bound, denoted LB2, that will be used to assess the performance of H+ when all network states are considered. In order to estimate a lower bound, we consider the best case in each failure scenario, because we want to minimize the overall number of blocked WPs. That means that, during a link failure, all the reliable WPs using the failed link are rerouted while the permanent ones are blocked. Since $a_{ij}$ is set to

one for all links $(i,j) \in M$, the cost of a WP also refers to the maximum number of failures that can affect the WP. Therefore, to estimate the lower bound, we have to multiply the number of blocked WPs in the no failure network state by the number of scenarios, and then added the sum of all the optical distances of the permanent WPs, denoted $n^P$, such that $n^P = \sum_{k \in K^P} d^{kt_0}_{D(k)}$. The lower bound, denoted LB2, is given below.

$$\sum_{t \in T} \sum_{k \in K} b^{kt} \geq |T| \times \sum_{k \in K} b^{kt_0} + n^P \tag{18}$$

TABLES VII to IX present the values obtained with H+ and LB2.

TABLE VII
NUMBER OF BLOCKED WPS (TEST NETWORK N3, $p = 0,1$)

| Number of wavelengths per link | Number of blocked WPs | |
|---|---|---|
| | H+ | LB2 |
| 1 | 1573 | 1482 |
| 2 | 1324 | 1118 |
| 4 | 809 | 572 |
| 8 | 357 | 78 |

TABLE VIII
NUMBER OF BLOCKED WPS (TEST NETWORK N3, $p = 0,2$)

| Number of wavelengths per link | Number of blocked WPs | |
|---|---|---|
| | H+ | LB2 |
| 1 | 3368 | 3276 |
| 2 | 2988 | 2782 |
| 4 | 2354 | 1950 |
| 8 | 1465 | 832 |

TABLE IX
NUMBER OF BLOCKED WPS (TEST NETWORK N4, $p = 0,1$)

| Number of wavelengths per link | Number of blocked WPs | |
|---|---|---|
| | H+ | LB2 |
| 1 | 5219 | 5130 |
| 2 | 4631 | 4370 |
| 4 | 3878 | 3382 |
| 8 | 2696 | 2166 |

The following observations can be made from TABLE VII to IX. First, algorithm H+ finds solutions close to the lower bound values for the problems considered (within 12,99%, on average, from the lower bound). For all the tests, the larger CPU execution time was 614 seconds, obtained with test network N7.

## 5 Conclusions and Further Works

In this paper, we have proposed a model for the RWA problem considering both permanent and reliable WPs. The proposed model deals with the routing and the wavelength assignment for the permanent and reliable WPs for the normal state of the network and for the important failure scenarios. Heuristic algorithms are proposed, H and H+. Algorithm H+ includes a proposed WA post-optimization algorithm that could be applied to any WA algorithms.

All the heuristic results were compared to proposed lower bounds, LB1 and LB2. These results have shown that the H+ heuristic produces solutions relatively close to the lower bounds for the test problems considered.

Several avenues of research are open at this point. For instance, it would be interesting to obtain better bounds to assess more accurately the quality of the solutions found with H+ for

large-size instances of the problem. Moreover, a new index could be defined to improve the post-optimization algorithm.

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